Constraints on Galactic Cosmic-Ray Origins from Elemental and Isotopic Composition Measurements

W.R. Binns[1], E.R. Christian[2], A.C. Cummings[3], G.A. de Nolfo[2], M.H. Israel[1], R.A. Leske[3], R.A. Mewaldt[3], E.C. Stone[3], T.T. von Rosenvinge[2], M.E. Wiedenbeck[4]
[1]*Washington University, St. Louis, MO 63130 USA*
[2]*NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA*
[3]*California Institute of Technology, Pasadena, CA 91125 USA*
[4]*Jet Propulsion Laboratory, Pasadena, California Institute of Technology, CA 91109 USA*

The most recent measurements by the Cosmic Ray Isotope Spectrometer (CRIS) aboard the Advanced Composition Explorer (ACE) satellite of ultra-heavy cosmic ray isotopic and elemental abundances will be presented. A range of isotope and element ratios, most importantly $^{22}Ne/^{20}Ne$, $^{58}Fe/^{56}Fe$, and $_{31}Ga/_{32}Ge$ show that the composition is consistent with source material that is a mix of ~80% ISM (with Solar System abundances) and 20% outflow/ejecta from massive stars. In addition, our data show that the ordering of refractory and volatile elements with atomic mass is greatly improved when compared to an ~80%/20% mix rather than pure ISM, that the refractory and volatile elements have similar slopes, and that refractory elements are preferentially accelerated by a factor of ~4. We conclude that these data are consistent with an OB association origin of GCRs.

1. Introduction

The study of the origin of galactic cosmic rays has always been understood to consist of two components: the source of acceleration and the source material that is accelerated. Cosmic-ray and gamma-ray measurements are providing important and complementary information relevant to understanding the origin of galactic cosmic rays [1]. Recent gamma-ray observations have identified gamma-rays consistent with hadronic acceleration coming from the core-collapse supernova remnants (SNR) W44 and IC443 [2], and distributed emission, also consistent with hadronic acceleration, from a "cocoon" that corresponds to the Cygnus superbubble extending from Cygnus OB2 to NGC 6910 [3]. Other SNR gamma-ray sources consistent with hadronic acceleration, all but one of which are the remnants of core collapse SNe, are discussed in [4]. Thus, the gamma-ray observations appear to have identified specific acceleration sites, which are primarily the remnants of core-collapse supernovae (SN). Since cosmic rays are charged particles, they do not point back to the source as gamma rays do, but the elemental and isotopic abundance patterns can identify the pool of material that is being accelerated and can "point" to the classes of objects that provide this source material.

The ACE-CRIS experiment was originally designed to measure the elemental and isotopic abundances of cosmic ray nuclei with charge (Z) $4 \leq Z \leq 30$ [5]. Owing to the long duration of the ACE mission and the large geometrical factor of the CRIS instrument, we have been able to collect a sufficiently large number of events so that measurements of elemental and isotopic abundances beyond the original design limits of the instrument are possible. We have obtained measurements of the isotopic abundances of nuclei through $_{32}Ge$ and elemental abundances, for the most abundant elements, through $_{38}Sr$. In this paper we present these results and show that they are consistent with a cosmic ray origin in which the source material consists of a mixture of ~80% ISM (with Solar System abundances[6]) and 20% outflow/ejecta from massive stars. This

is consistent with galactic cosmic rays originating in associations of massive stars (OB associations) and the superbubbles that they form.

2. Measurements of Ultra-heavy Elements

Figure 1 is a histogram of elements from $_{25}$Mn through $_{40}$Zr. We have obtained excellent resolution in charge over the full range plotted, as can be seen from the figure, with limited statistics at the highest charges. The numbers of events obtained are comparable to those obtained by the TIGER instrument [7].

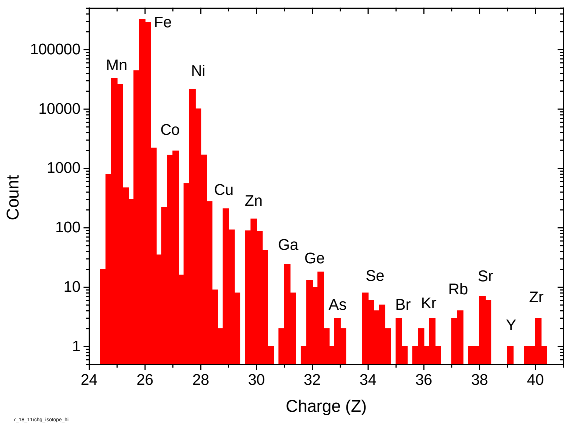

Figure 1—Histogram of elements

Figure 2 shows our measured elemental abundances relative to iron compared to TIGER and HEAO-C2 abundances. We see that there is generally good agreement between the measured abundances. The solid line is a plot of solar system abundances [6] relative to iron. Perhaps the most striking observation from this plot is that the abundances of $_{31}$Ga and $_{32}$Ge are very similar in our data, while in the solar system $_{32}$Ge is ~3x more abundant than $_{31}$Ga. Woosley and Heger [8] show that for combined outflow and ejecta of massive stars, $_{31}$Ga has the largest "overproduction factor" relative to solar system abundances of any element. Thus, we may very well be seeing a nucleosynthetic signature of massive star origin in the cosmic ray elemental abundances.

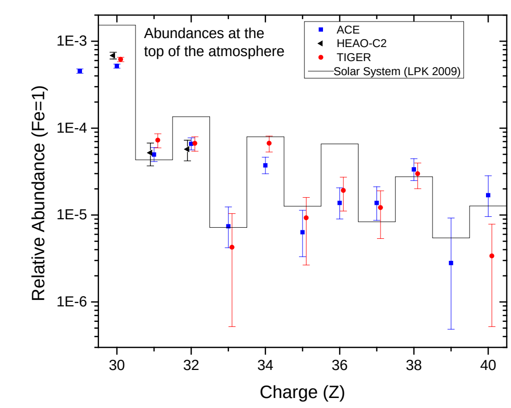

Figure 2—Elemental abundances relative to iron compared to solar system abundances

In Figure 3 we plot the cosmic ray source abundances derived from our measurements relative to a mix of ~20% massive star outflow plus supernova ejecta [9] and ~80% normal ISM (with solar system abundances) versus atomic mass. We see that the volatile and refractory elements (elements that reside in the gas phase and as interstellar grains respectively in the ISM) are nicely separated, with refractory elements having an abundance ~4x greater than volatile elements. In addition, their slopes are very similar. The ordering of refractories and volatiles is greatly improved over that obtained by a similar plot of element abundances relative to 100% normal ISM versus atomic mass [10,7]. We take this very significant improvement in ordering to indicate that the pool of material from which cosmic rays

originate is mixture of ~20% massive star outflow and ejecta with ~80% normal interstellar medium material. The elemental abundances measured by ACE-CRIS are in generally good agreement with the TIGER results [7]. We note that the abundances of Cu-Kr measured by CRIS are systematically slightly lower than in the TIGER data, even after allowing for a known effect of exceeding the dynamic range for high-Z particles with large incidence angles, for which we have made corrections. To this point we have not been able to show any mechanism which has resulted in such a bias. Work is on-going to study the possibility of a systematic bias for UH elements.

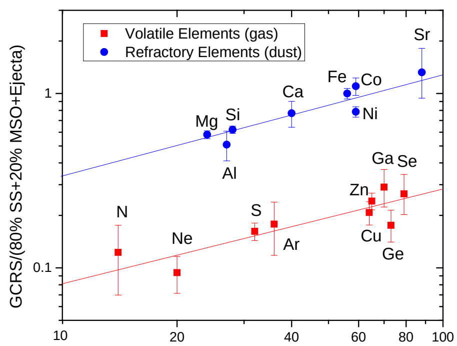

Figure 3--Element source abundances relative to a 20%-80% mixture of massive star material and ordinary ISM plotted vs. atomic mass

3. Measurements of Ultra-heavy Isotopes

Figure 4 is a histogram of isotopes extending from $_{27}$Co through $_{34}$Se. We see well resolved isotope peaks from $_{27}$Co through $_{32}$Ge with sufficient statistics for a meaningful measurement. In Figure 5 we have plotted our measured isotope source abundances relative to solar system over a broad range of charges. The black data points (circles) of ratios from $_{10}$Ne to $_{28}$Ni were reported previously [11] and led to the conclusion, in agreement with Higdon and Lingenfelter [12], that the likely source of a substantial fraction of galactic cosmic rays (GCR) is clusters of massive stars called OB associations and their associated superbubbles [11-13]. The red data points show our recent preliminary measurements of the isotopes of $_{29}$Cu through $_{32}$Ge. The solid line in the figure was obtained using a two component model in which outflow from stars with sufficient mass to evolve into Wolf-Rayet stars (>~30Mo) [9] was mixed with normal interstellar medium material (with solar system abundances) such that the modeled ^{22}Ne/^{20}Ne ratio was normalized to our measured ratio [11,13]. The mix required for this normalization was ~20% massive star outflow plus ~80% normal interstellar material (ISM). For that mix, the model then predicts the abundances that we should see for other ratios (solid line). We see that our abundance ratios for $_{29}$Cu through $_{32}$Ge are consistent within the error bars with the mixture, but they are also consistent with solar system abundances; i.e. they do not discriminate between the source material being pure ISM or the 80%-20% mix. Thus, these improved ($_{29}$Cu and $_{30}$Zn) and new ($_{31}$Ga and $_{32}$Ge) measurements are not inconsistent with a GCR origin in OB associations and their associated superbubbles.

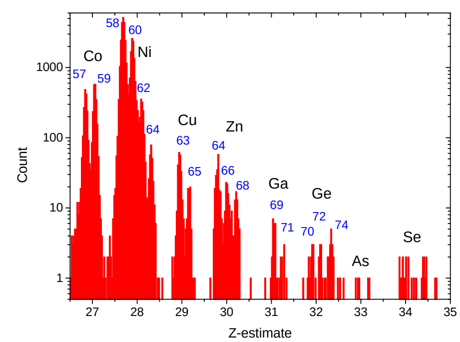

Figure 4—Histogram of isotopes showing clear isotope peaks up through $_{32}$Ge

It also appears that we have resolved isotopes as high as $_{34}$Se, although additional statistics are needed to obtain clearly resolved peaks. For $_{34}$Se the tentative mass numbers assigned to the "clumps" of particles have about the right spacing, but clear peaks, which require more particles, would help to confirm the mass identification. Additional data and careful analysis of events that have been rejected in our current data set, with the possibility of reclaiming some of them, might result in clear peaks and mass assignments. This would provide another isotope group that could be used to test models of cosmic ray origin.

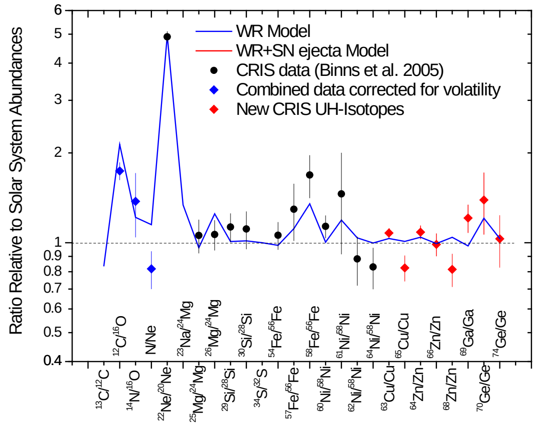

Figure 5--Plot of isotope and element ratios relative to solar system abundances. The solid line was obtained by mixing massive star outflow material [10] with normal ISM until it matched our measured $^{22}Ne/^{20}Ne$ ratio.

4. Conclusions

We conclude that the elemental and isotopic abundances of galactic cosmic rays provide strong constraints upon the GCR source. The substantial improvement in ordering of the refractory and volatile elements when compared to the 20%--80% massive star/ISM mixture, instead of normal ISM alone, points to cosmic ray origin in OB associations. Furthermore, the agreement of the isotopic abundances with a similar mixture gives a completely independent indication that OB associations are the likely source of a large fraction of galactic cosmic rays.

References

1. W.R. Binns, Science 334 (2011) 1071
2. M. Ackermann, et al., *Science* 339 (2013) 807
3. M. Ackermann, et al., Science 334 (2011) 1103
4. C.D. Dermer and G. Powale, A&A 553 (2013) A34
5. Stone, E.C., et al., Space Sci. Rev. 86, 285, 1998.
6. Lodders, K., ApJ 591, 1220, 2003.
7. Rauch, B.F., et al., ApJ 697, 2083, 2009
8. Woosley, S.E., & A. Heger, Phys. Rpts. 442, 269,2007
9. Meynet, G., & A. Maeder, A&A, 404, 975, 200
10. Ellison, D.C, et al., ApJ 487, 197, 1997
11. Binns, W.R., et al., ApJ 634, 351, 2005
12. Higdon, J.C. & R.E. Lingenfelter, ApJ 590, 822, 2003
13. Binns, W.R., et al., New Astron. Revs. 52, 427, 2008